Institute for Energy Economics and Financial Analysis

The carbon dioxide disposal chain: Elements, goals and risks

J. Grant Hauber
Strategic Energy Finance Advisor, Asia

Kuala Lumpur, Malaysia

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Accelerating the Energy Transition in Asia

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What are the components of the CCS disposal chain?

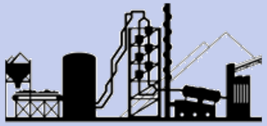
CCS/CCUS: some common understandings

“U” in CCUS =	“Utilization” is for enhanced oil or gas production in >95% of the cases. Other CO_2 utilization options lack scale.
“Storage” =	CO_2 is forced into pore spaces, not stored in caverns. Goal is to trap or chemically bond CO_2 with rock.
“U” vs “S” =	If you are ‘utilizing’ CO_2, you are not storing it. If you are ‘storing’ CO_2, you are trying to dispose of it.
How disposed? =	CO_2 is compressed into a ”supercritical state”, somewhere between liquid and gas, its densest form. This is injected at high pressure (~700atm/10,000psi) a minimum of 800m below the surface.

CCS disposal is not one activity, but a string of separate projects

Capture | **Separation/ Purification** | **Compression for Transport** | **Transport** | **Compression for Injection** | **“CCU” = Subsurface EOR/EGR**

Refining/Petchem
60%-80%?



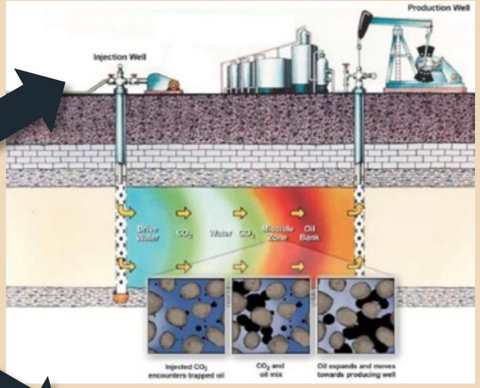
Cement/Industrial
20%-60%?

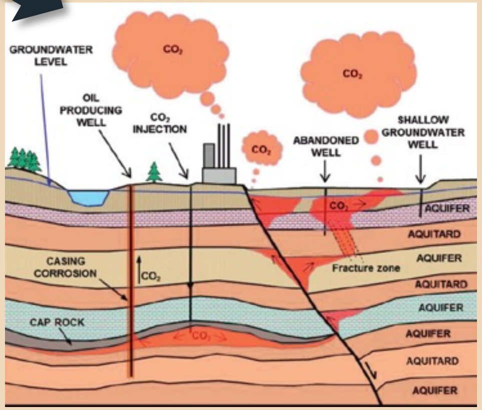
Coal/Gas Power Gen
30%-60%?

Pipeline

Shipping

+ Ports





Upstream Project | **Midstream Project** | **Storage Project**

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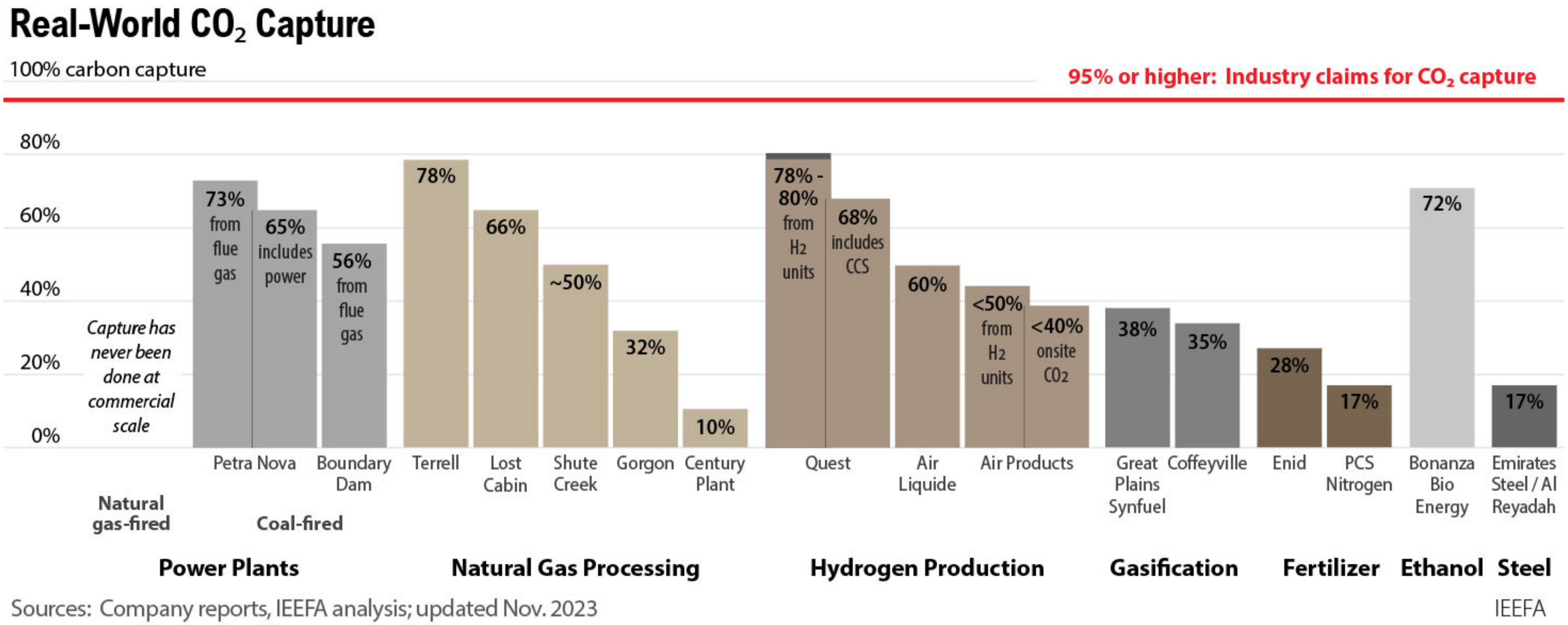
What are the performance and risks characteristics of the CCS disposal chain?

CO_2 Capture: Real-world data shows carbon capture efficacy rates vary widely, none even close to 90%



IEEFA. Blue Hydrogen: not clean, not low carbon, not a solution. September 2023 [updated November 2023].

CO_2 purity requirements for CCS are high

Contaminants change CO_2 properties

- Accelerated corrosion
- Changes liquid-gas point, density

CO_2 needs pre-processing to remove gasses, H_2S, heavy metals

- Filtration byproducts need proper disposal

Emerging risk issue: mixed CO_2 quality
CO_2 "hubs" propose to accept a wide range of CO_2 effluents, much like a garbage dump

- These gases must be homogenized
- Increased risk to storage integrity, equipment

CO_2 Grade	Purity	Other Gases
Research	99.999%	<0.001%
Super-critical fluid	**99.998%**	<0.002%
Laser	99.95%	<0.05%
Food & Beverage	99.9%	<0.1%
Bone Dry	**99.8%**	<0.2%
Medical	99.5%	<0.5%
Industrial	99.5%	<0.5%

Injection Grade: Super-critical fluid

Pipeline Grade: Bone Dry

Source: adapted from CO2 Meter Gas Measurement Specialists. Carbon Dioxide Purity Grade Chart. February 22, 2024.

CO_2 Pipelines

Only 14,500 km of CO_2 pipelines exist

- 8,000 km of those in the US
- Comparison: 2.4 million km of fossil gas pipelines worldwide, 1.6 m km of which are in the US

Challenging permitting, extensive implementation timeframes

- CO_2 pipelines structurally must be underground

CO_2 pipelines need higher quality/higher cost alloy steels due to corrosion potential

Moisture of only 50ppm can create acids

- Serious pipe corrosion can take place within hours

CO_2 is heavier than air

- Leaks displace oxygen at ground level, high human risk

Denbury CO_2 pipeline rupture, Satartia, Mississippi, February 2020.
Source: Huffington Post, April 2021.

CO_2 Shipping

Vessels do not currently exist, must be built

- Design considerations limit carriers to small sizes – e.g. 7,500m^3 for Norway's Northern Lights

Higher CO_2 purity needed

- 99.9%, <30ppm water

"Boil-off" of liquid CO_2

- Gasifies at 0.15% per day; ships traveling long distances may require reliquification plants

Design safety considerations

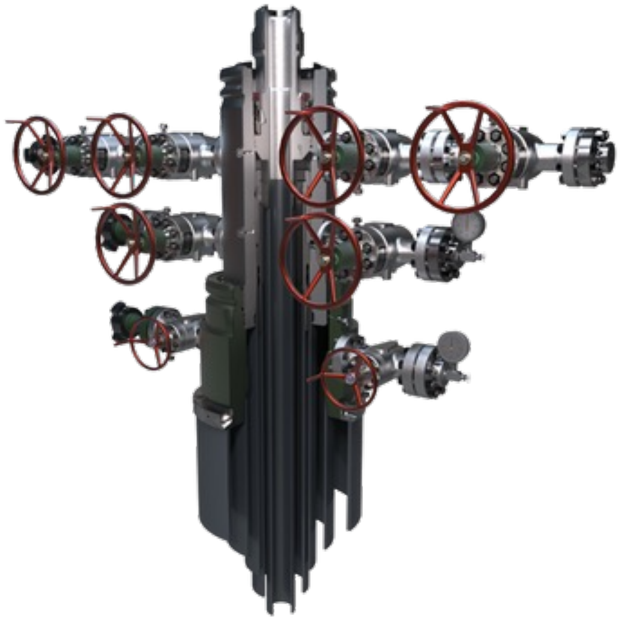
- Specialty materials and designs
- Cannot be used to carry any other commodities

Challenging economics

- Small scale and specialty operating requirements mean high cost per tonne-km.
- Specially designed and configured ports

Cross-border carbon accounting issues

Subsurface CO_2 injections are unlike oil & gas industry equivalents



- CO_2 is injected as a super-critical fluid, its highest density
- Super-critical CO_2 must be ultra-high purity, >99.998%, meaning <3ppm water
- Well design is much more stringent when handling CO_2
    - Specialized alloy drill casings, gaskets and high specification cements
- Wellhead fittings and equipment need to be specifically designed and certified to handle CO_2
    - CO_2 fittings must withstand higher temperature and pressure ranges than oil and gas standards
- Much of these fittings and equipment remain in R&D stage
- Maintenance cycles shorter, more critical

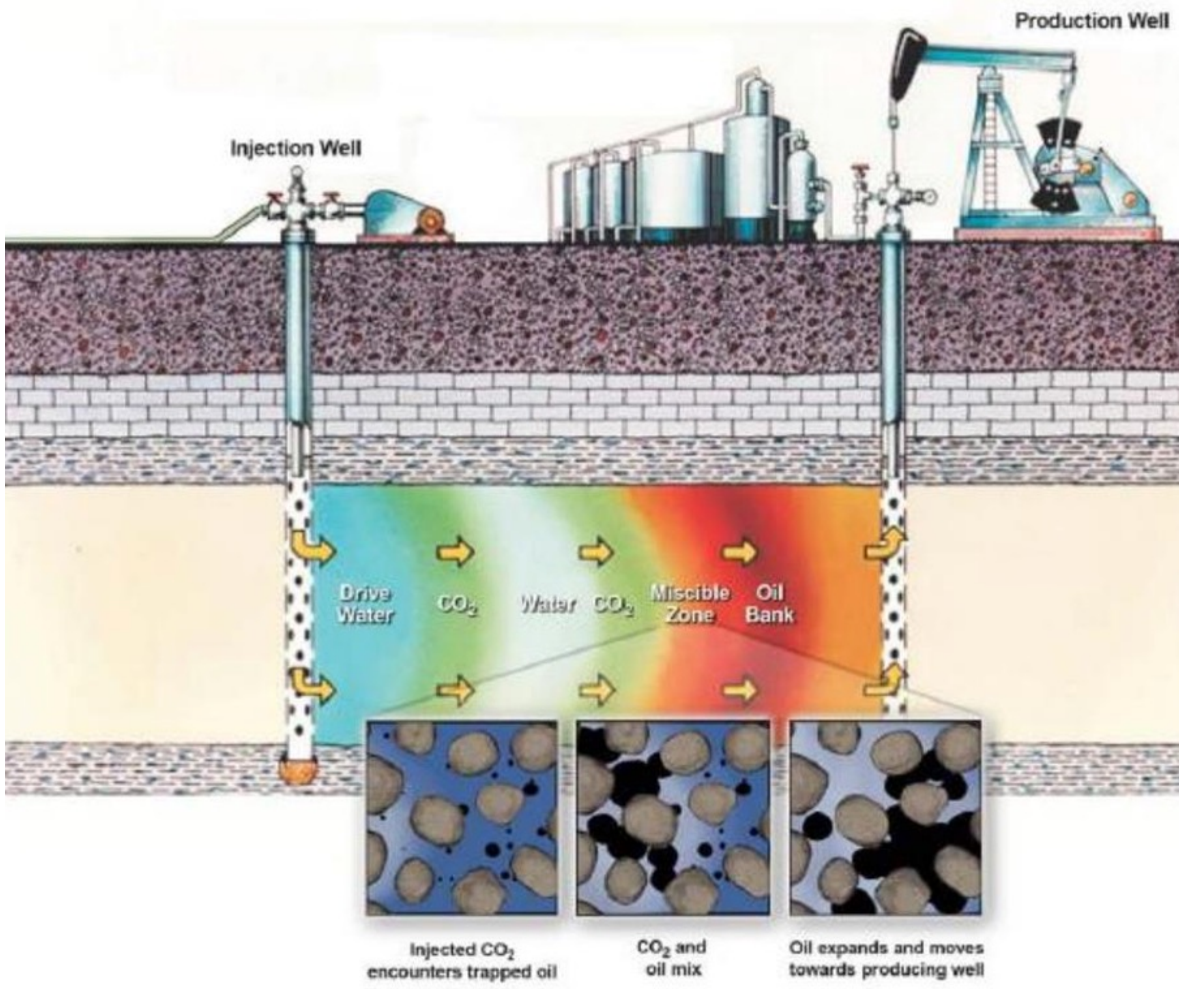
CC*U* is for hydrocarbon production, not CO_2 storage

Enhanced oil and gas production is the main purpose of CCUS.

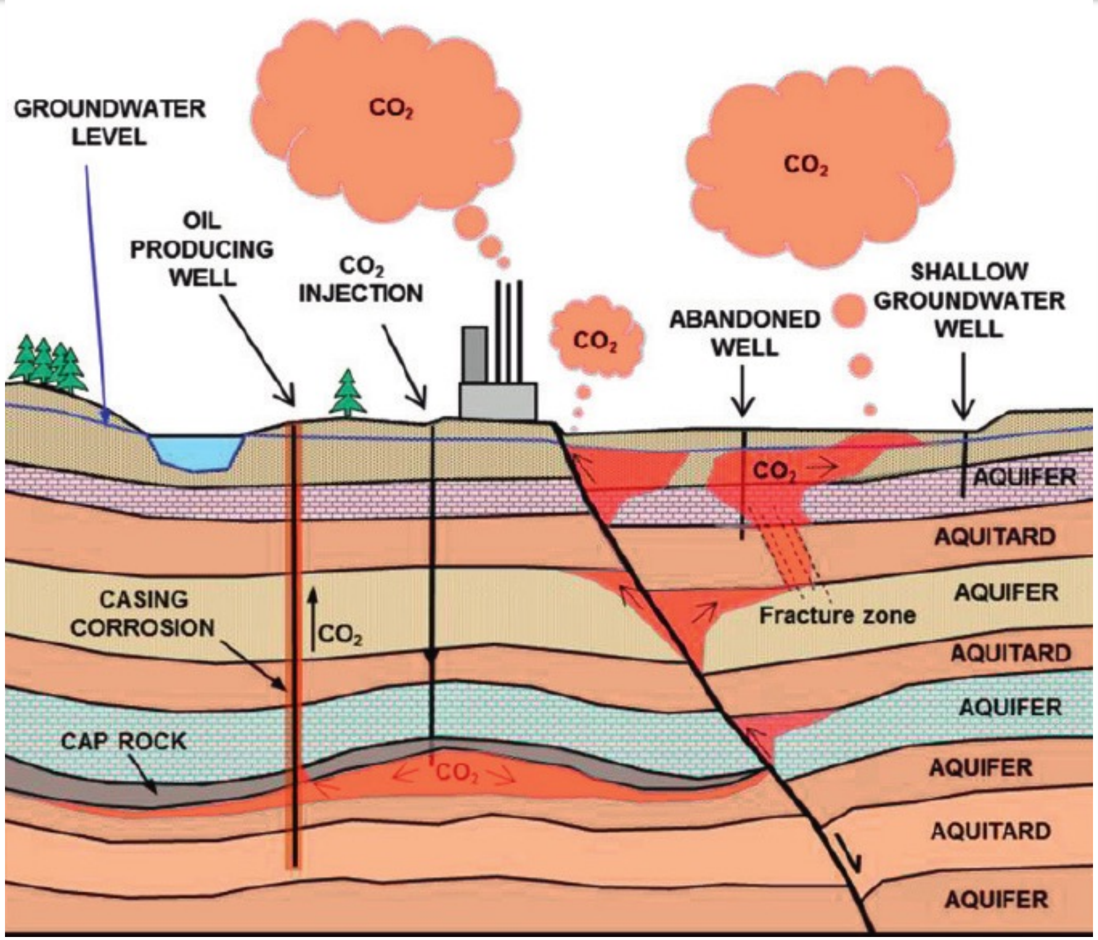
EOR/EGR projects have open communication between CO_2 injection point and oil/gas extraction point.

CO_2 trapping is a *possibility*, but not assured.

Highly perforated oil/gas production fields are suboptimal for permanent storage as they are designed to release hydrocarbons, not trap them.



Subsurface CO_2 storage risks abound and can present at any time

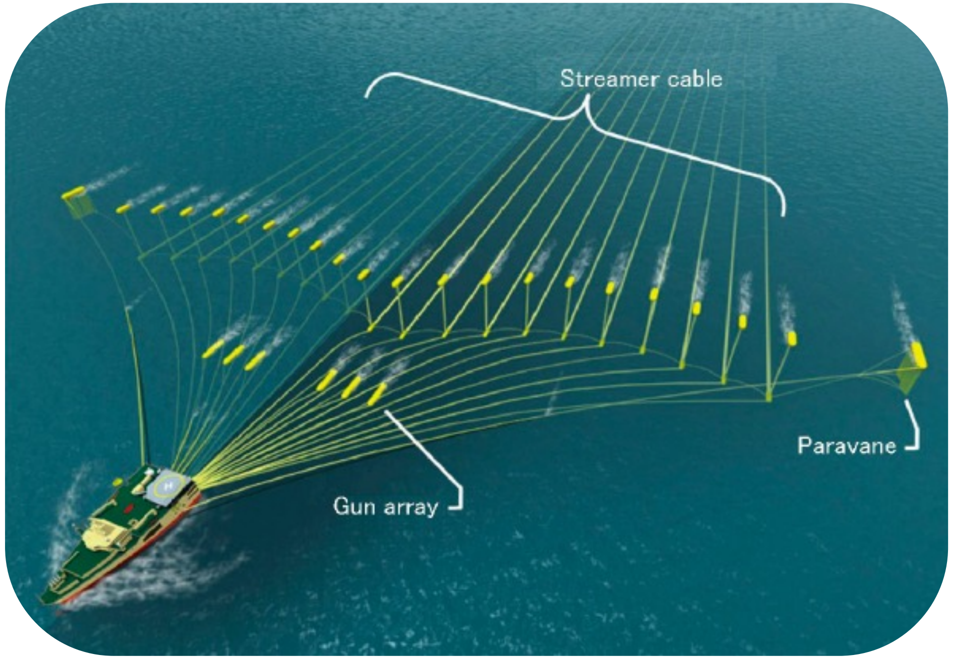


CO_2 behavior won't be known until it is put into the ground, regardless of prior survey, engineering or lab work that goes into site design and preparation

- CO_2 rejected by subsurface geochemistry
- Phase change from supercritical fluid to gas
- Finds undetected faults or subsurface anomalies
- Finds abandoned wells
- Induces corrosion around well casings
- High pressures compromise storage geology
- Induced seismicity affecting surface
- Problems may materialize for many years
- CO_2 underground may not stabilize for decades or centuries, creating high risk, long-term liabilities

Even minor leakage rates undermine the permanent climate premise of CCS.
CO_2 storage needs to be more like nuclear waste security with zero loss tolerance.

Q: How do scientists / operators know what is happening to CO_2 in storage?



A: Estimates and models

Only how much CO_2 was injected is known

Operators can only *estimate* how much CO_2 is retained

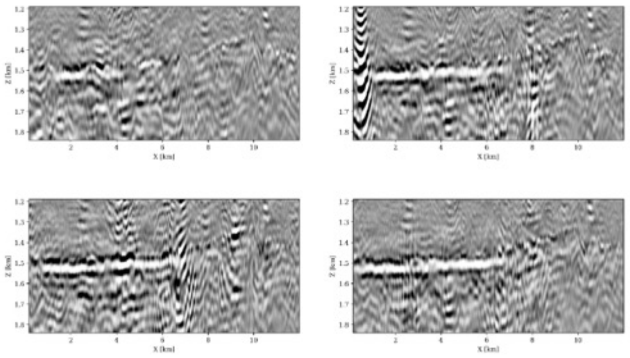
Verification measurements are made very infrequently

- Can be years in between
- Even then only a snapshot in time
- Large changes/movements can take place

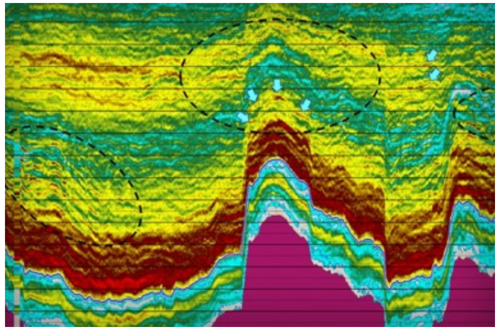
CO_2 volume stored is estimated from data and models

…the models are getting better…

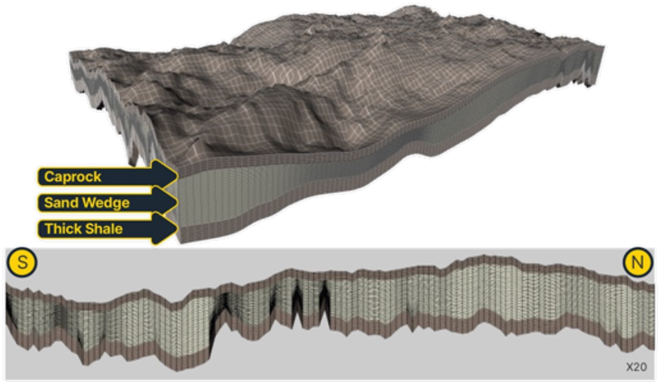
2007



2009

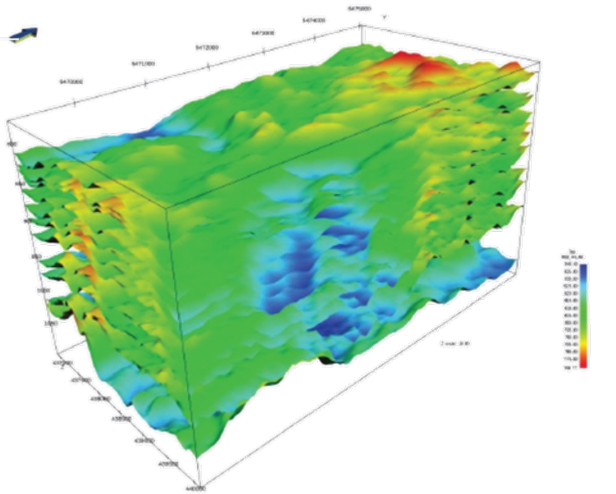


2011



Source: Energy Procedia. Benchmark calibration and prediction of Sleipner CO_2 plume from 2006 to 2012. Cavanagh. Volume 37. 2013, p. 3529-3545. 2013.

2019



Source: Equinor. Sleipner Benchmark 2019. CO_2 DataShare. October 2022.

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…but only monitoring of CO_2 possible.
CO_2 cannot be controlled once in the ground.

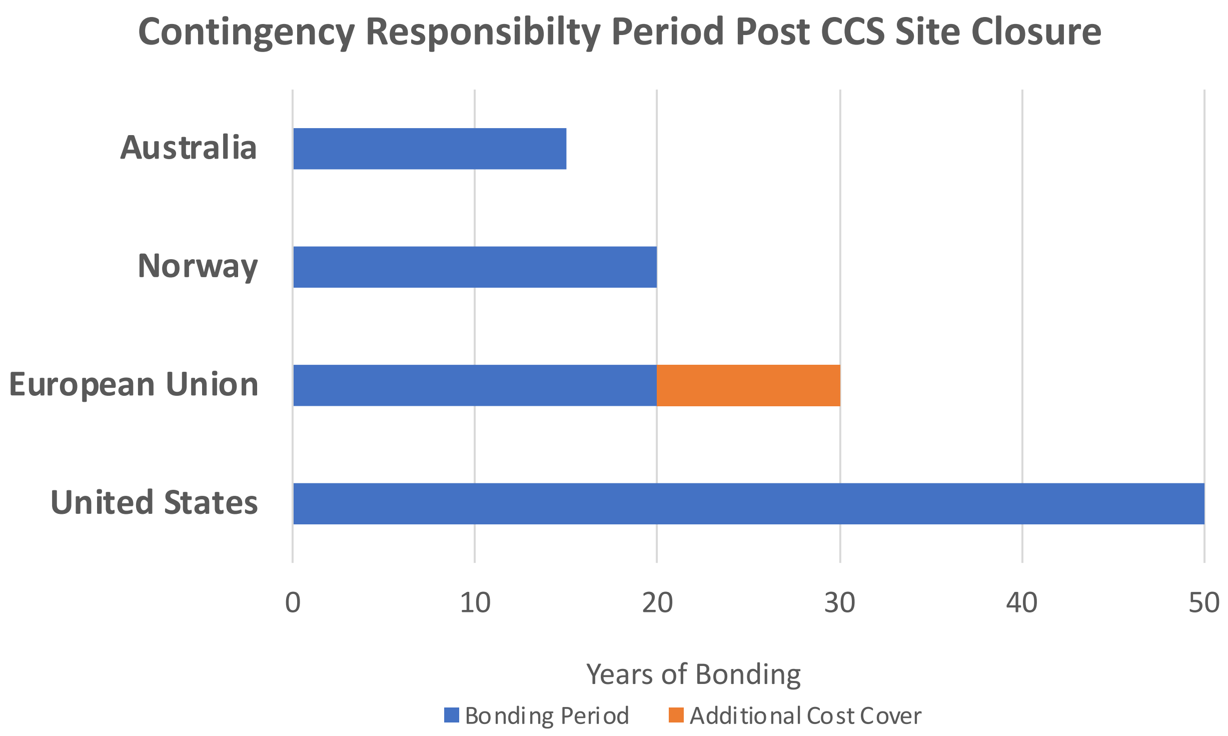
CO_2 storage monitoring, verification, regulation

Regulatory frameworks for storage are nascent

- What to monitor? How to monitor?
- Frequency of measurement? Details of reporting level of confidence?
- Regulator skills and staffing lacking to adequately interpret and intervene.

Operator responsibility period is very short

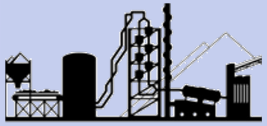
- In all cases, operator responsibility is far shorter than the physical stabilization period for CO_2
- State assumes all responsibility after the performance period expires,
  - Monitoring, protection, and intervention (if needed) – and all costs



CCS disposal chain: cost and risk at every step, CO_2 still emitted

Capture | **Separation** | **Purification** | **Compression for Transport** | **Pipeline** | **Compression for Injection** | **Subsurface EOR/EGR**

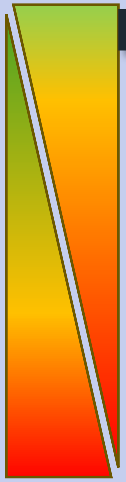
Refining/Petchem
60%-90%?



Cement/Industrial
40%-75%?

Coal/Gas Power Gen
30%-60%?

High CO_2



High Cost

Efficacy ranges widely based on CO_2 source concentration: <10% to <80%?

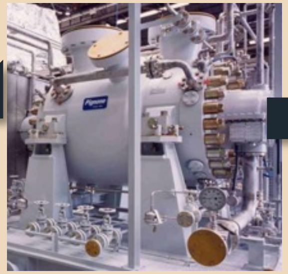
Realities:
Off-gas 0.5-3%

Risks:
Operation-related venting, line losses, corrosion, higher maintenance rates vs NG

Realities:
Leakage 0.5-1%

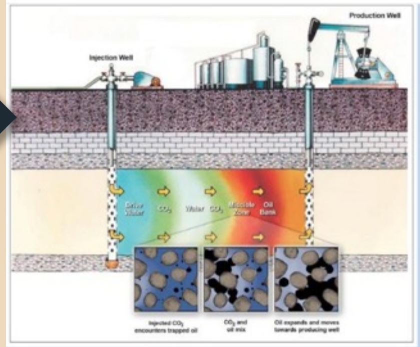
Ships and Ports

Realities:
Boil-off 0.15%/d
Transfer leaks

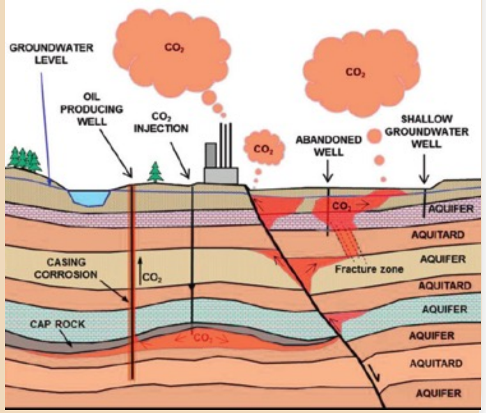


Realities:
Off-gas 0.5-3%

Risks:
Blowout due to ultra high pressure.
Corrosion, higher maintenance rate



Subsurface Disposal



Project-on-project risk → **Upstream Project** | **Midstream Project** | **Storage Project**

CCS disposal chain is highly challenged

1

Need for integrated disposal chain investment

Project on project risk, multiple parties responsible

2

Need for new designs and technologies for safety, security

Many are still in R&D stage, or untested at commercial scale

3

Disposal sites each are unique and possess great unknowns

Not certain how secure storage is, what to do if there are leaks

4

Regulation and oversight are highly technical and long duration

CO_2 stabilization periods are likely far longer than operator's responsibility

5

Financial economics are challenged due to lack of clear carbon price

CO_2 is effectively a waste product of little value yet incurs high costs

Thank you!

J. Grant Hauber

Strategic Energy Finance Advisor, Asia

ghauber@ieefa.org

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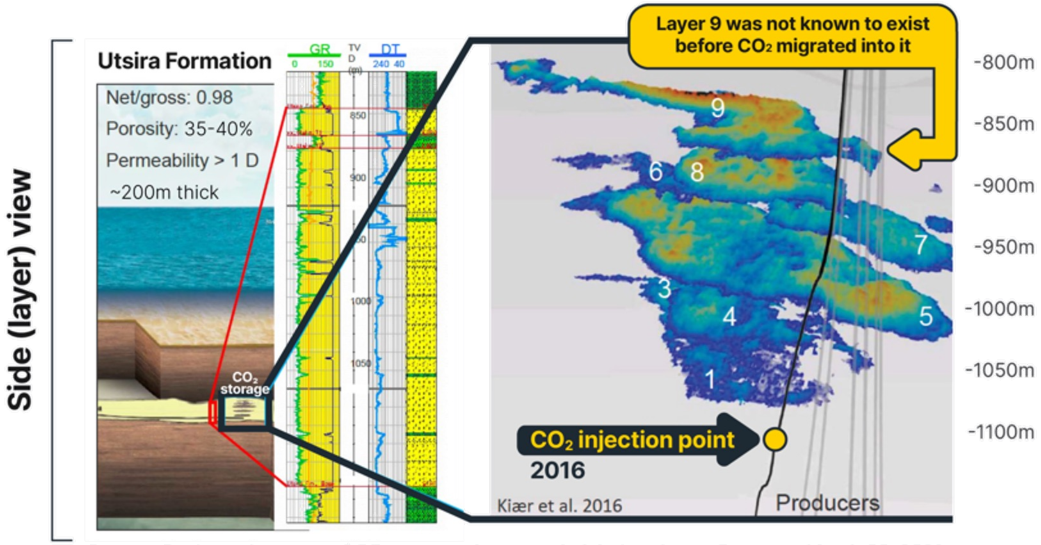
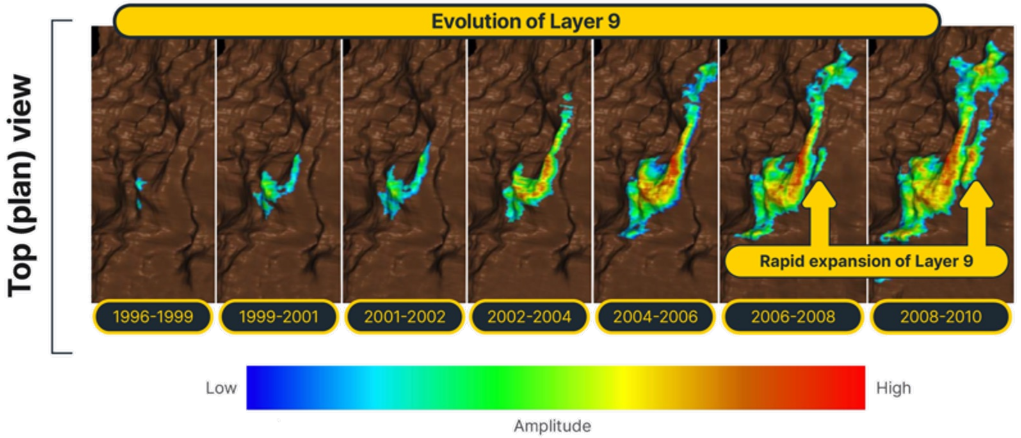
Support Materials
Subsea Storage

Sleipner: 8 CO_2 storage layers quickly become 9

- Original geophysics concept: CO_2 would gradually percolate up through several shaly layers over a period of many years
- Configuration identified through preliminary seismic studies, calculations
- Instead, in less than three years, CO_2 moved all the way to shallowest caprock
- CO_2 accumulated in a previously unidentified layer 9, circa 800m – risk of super-critical CO_2 becoming gaseous
- At some point after 2004, this accumulation grew large and began migrating west towards the UK border
- The horizontal boundaries of Layer 9 remain unknown; no way to stop movement

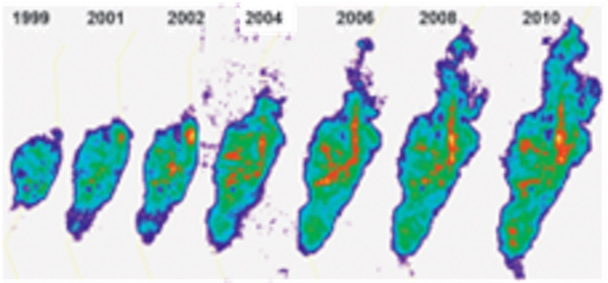


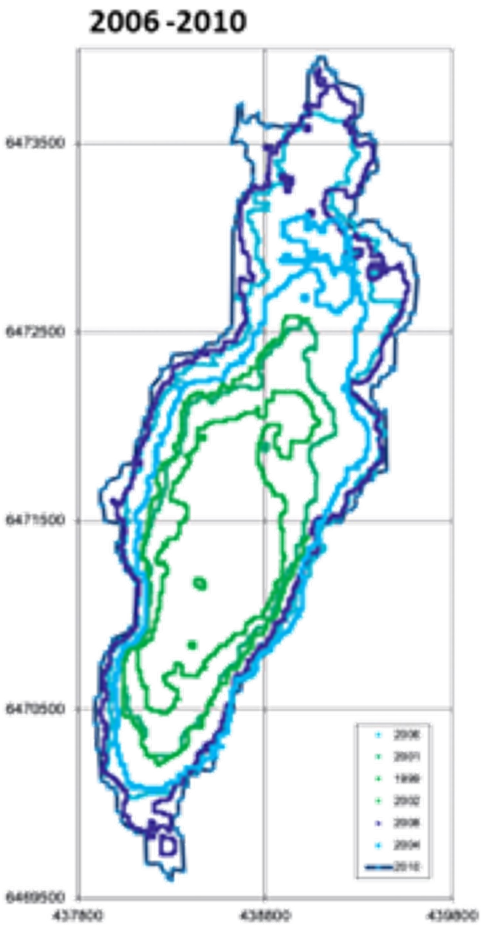
Source: Geological storage of CO_2: project design and global scale-up. Ringrose. March 29, 2021.

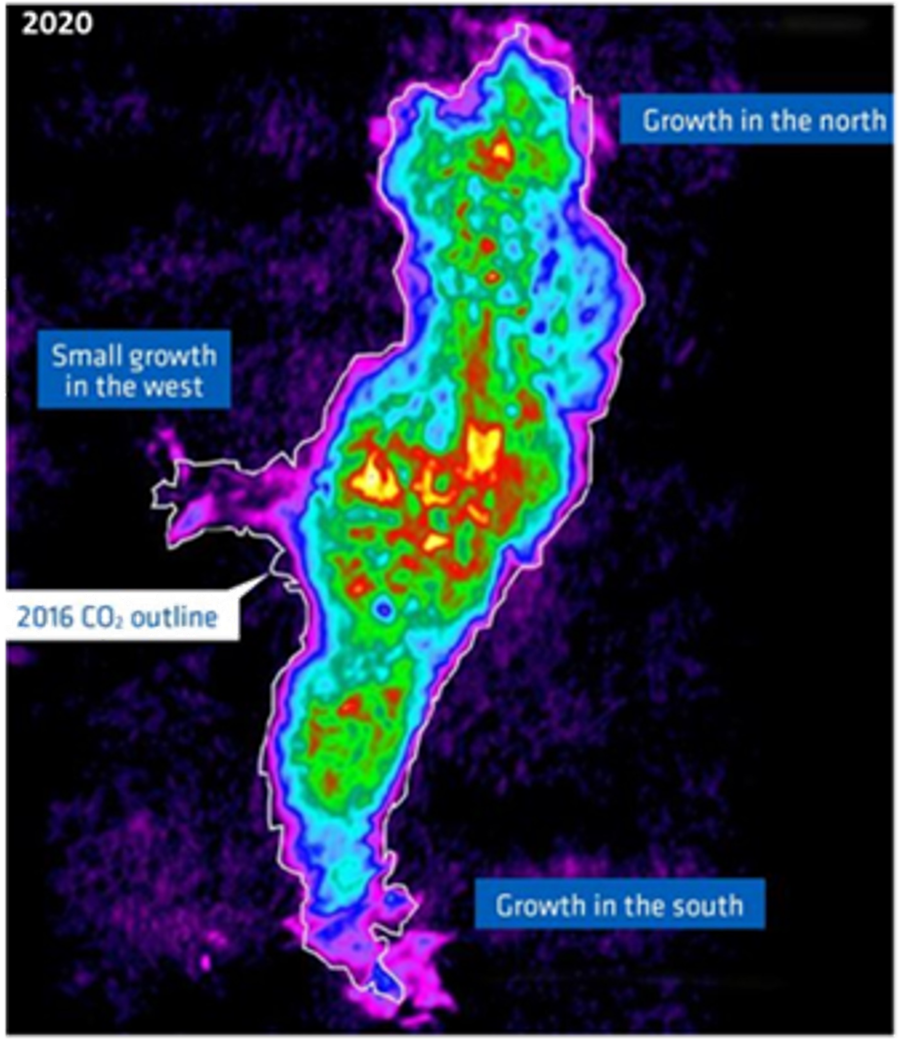


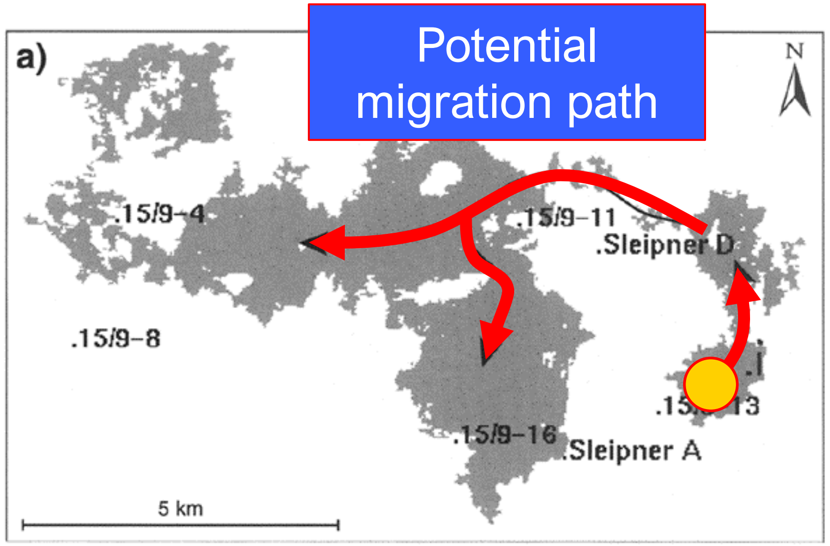
Source: Statoil ASA. Sleipner – 20 years of successful storage operations and key learning for future projects. Skalmeraas. June 29, 2016. IEEFA

And the shallow plume keeps moving…





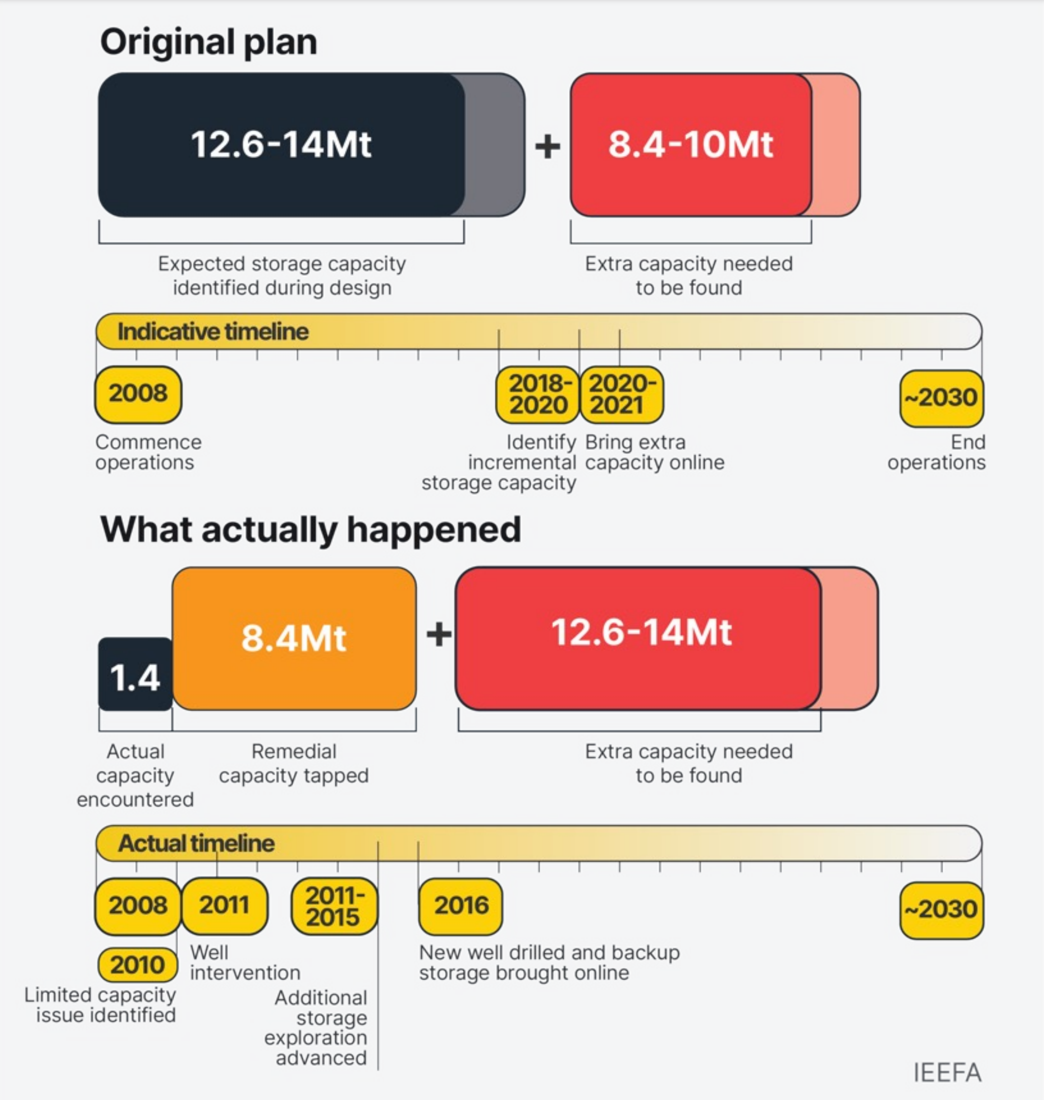




Snøhvit: Reduced storage capacity meant finding a new site

Original Plan

- Inject in safe formation underneath gas producing area
- Sufficient capacity for about 18 years of production
- Use time to find suitable follow-on storage space
- Switch over to new area once original layer is full



Remedial Plan

- Use a 'quick fix' layer for storage to resume operations
- New layer only good for about 4-6 years of operations, i.e. to ~2016
- Immediately prospect for new CO_2 storage, starting 2011
- Invest in developing new well and infrastructure, 2016
- Invested additional at least US$225 million

CO_2 storage conclusions, cautions

- Geologic variations on every site, thus each will be unique
  - No one site is a template for the next
  - The larger the site, the more chances for variations
- Even top-level science and engineering cannot know what will really happen to the storage site or CO_2 in it
- CO_2 underground can only be monitored, not controlled
- CO_2 can stay active for decades or centuries, thus the risk of loss containment remains
- A "minor leak" means CO_2 abatement benefit is lost, and subsidies or credits are for nothing

Norway's Sleipner and Snøhvit: industry models or cautionary tales?

Contacts

Author: Grant Hauber
Strategic Energy Finance Advisor, Asia
ghauber@ieefa.org

Media: Alex Yu
Editor and Communications Specialist
ayu@ieefa.org

Institute for Energy Economics and Financial Analysis

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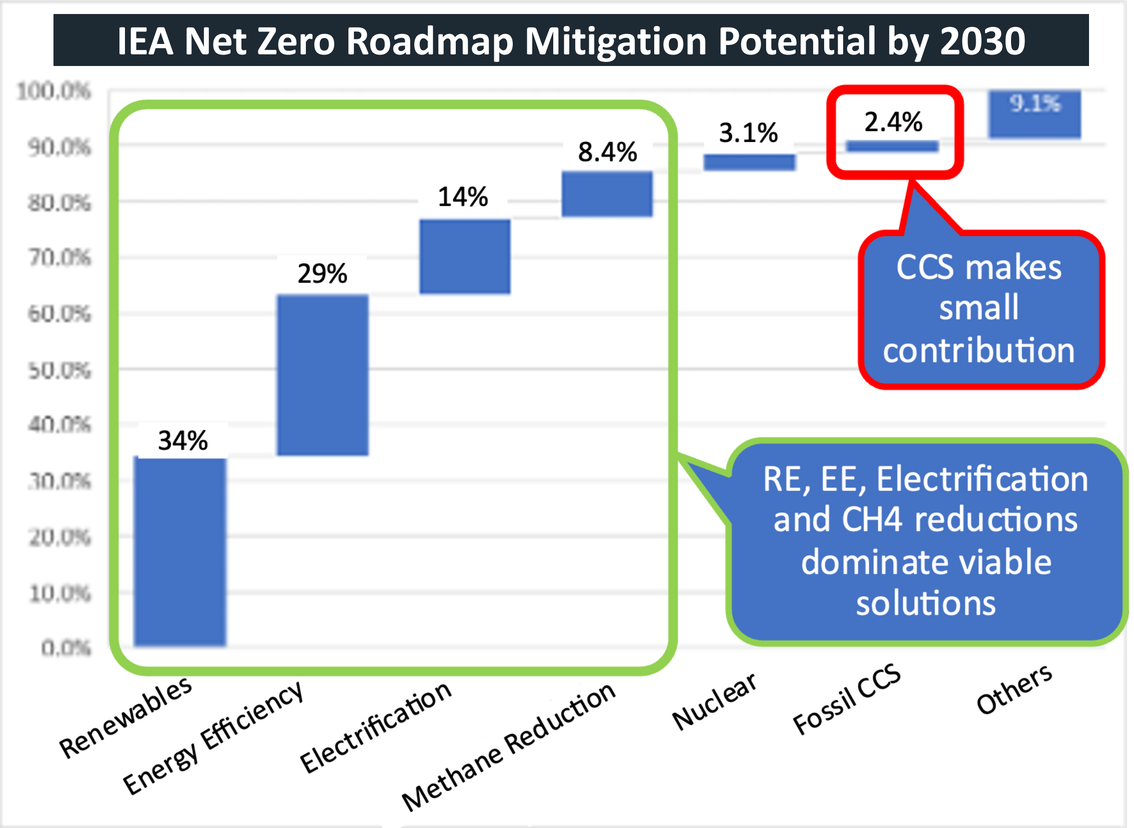
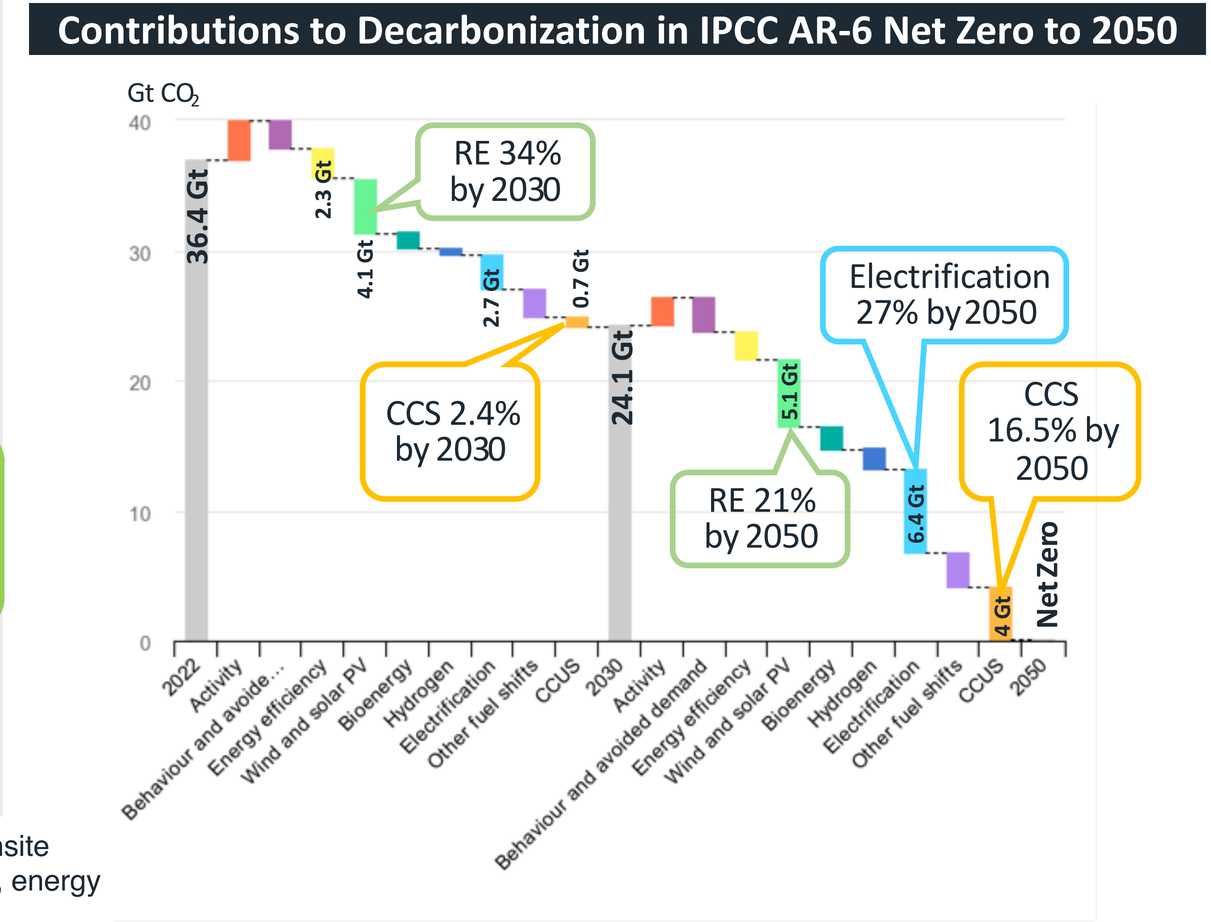
>80% of the decarbonization solution has nothing to do with CCS





Note: “Others” and “Other Fuel Shifts” refer to assorted lower carbon fuel switching, onsite energy provision derived from transformation of primary materials into useable energy, energy derived from wastes/byproducts, alternative fuels.
Source: IEA Net Zero Roadmap. September 2023, IPCC AR-6 Report, March 2023.
Left Graphic: E3G adapted from IEA NZR. Right Graphic: IEEFA adapted from IPCC-AR6.